Interference Analysis and Management for Spatially Reused Cooperative Multihop Wireless Networks

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***Abstract*— In this paper, we consider a decode-and-forward based wireless multihop network with a single source node, a single destination node, and N intermediate nodes. To increase the spectral efficiency and energy efficiency of the system, we propose a cooperative multihop communication protocol with spatial reuse, in which interference is treated as noise or can be canceled. The performance of spatial-reused space-time coded cooperative multihop network is analyzed over Rayleigh fading channels. In particular, the exact closed-form expression for the outage probability at the nth receiving node is derived when there are multiple interference sources over non-i.i.d. Rayleigh fading channels. Furthermore, the outage probability expressions are derived when nodes are equipped with more than one antenna. In addition, to reduce the effect of interference on multihop transmission, we propose a simple power control scheme which is only dependent on the statistical knowledge of channels. In the second approach for managing the interference, linear interference cancelation schemes are employed for both non-cooperative and cooperative spatial-reused multihop transmissions. Finally, the analytic results were confirmed by simulations. Simulation results show that the spatial-reused multihop transmission outperforms the interference-free multihop transmission in terms of energy efficiency in low and medium SNR scenarios.**

I. Introduction

Cooperative multihop wireless systems have been considered as the promising technique to extend coverage area and reduce power consumption [1], [2]. This technique relies on the concept of multihop diversity introduced in [3] where the benefits of spatial diversity are achieved from the concurrent reception of signals that have been transmitted by multiple previous terminals along the single primary route. This scheme exploits the broadcast nature of wireless networks where the communications channel is shared among multiple terminals. In [2], three cooperative multihop transmission protocols were proposed that compromise between spectral and energy efficiencies. Other variations of multihop diversity are studied in [4] and [5]. In [4], it is shown that a CDF-aware multihop diversity results a significant diversity gain over Nakagami-m fading channels. A buffer-aided multihop diversity scheme in [5] can be also exploited for enhancing the reliability of wireless multihop communications.

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To further increase of multiplexing gain and energy efficiency, in this paper, we consider a cooperative multihop transmission with interference due to the simultaneous transmission of multiple packets. The idea of multihop transmission with spatial reuse is proposed in [6]. To facilitate concurrent transmission of several packets in the network, the available bandwidth is reused among transmitters, with a minimum division of K nodes between simultaneously transmitting nodes. Therefore, we have to deal with a type of co-channel interference (CCI).

The performance analysis of multihop transmission in Rayleigh fading channels under CCI were recently studied in the number of literature such as [7]–[11]. In particular, the performance of a dual-hop relay network over CCI was studied in [12]–[14], while the multihop case was studied in [15], [16]. The impacts of imperfect channel estimation in such networks have also been studied in [17], [18]. For an arbitrary but fixed number of Nakagami-distributed interferers per hop, authors in [15] derive closed-form expressions for the outage probability of AF and DF relaying. In [16], the authors have investigated the asymptotic error probability for the channel state information (CSI)-assisted amplify-and-forward multihop over Nakagami-m fading channels in the presence of the CCI. Other related works include upper-layer game-theoretic studies such as in [19], [20]. However, to the best of our knowledge, this is the first work that investigate the performance analysis of multihop networks with multiple interferences over non-i.i.d. Rayleigh fading. This is of primarily importance for the study of interference due to spatial reused cooperative multihop transmission.

In this paper, we study the performance analysis of the decode-and-forward based cooperative multihop transmission with interference due to the concurrent transmission of multiple data. The capacity of the cooperative multihop transmission can be improved by using the spatial reuse scheme. The achievable rate of the multihop transmission can be increased up to $\lfloor \frac{N+1}{K} \rfloor$ times, where K is the minimum separation of concurrently transmitting nodes in a network with N relays, in expense of performance degradation. Moreover, we derive a closed-form expression for the outage probability of the cooperative multihop system in presence of interferences due to the spatial reuse over Rayleigh fading channels. The simplicity of the calculated expression can give insights on performance of the system and ways to optimize the system. In addition, the asymptotic formulas for different signal-to-noise ratio (SNR) and interference-to-noise ratio (INR) conditions are derived. Furthermore, we generalize the spatial-reused cooperative mul-

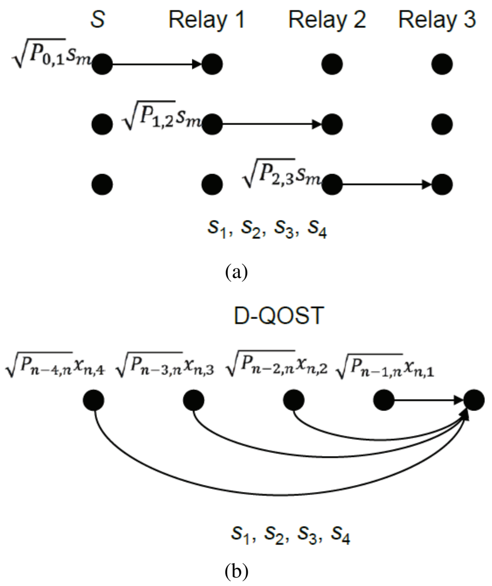

Fig. 1. Multihop-then-Cooperate Protocol: (a) Initial phases; (b) Subsequent phases using a distributed space-time code with $M = 4$.

tihop transmission to the case of nodes with more than one antenna. The outage probability expressions for the spatially-reused cooperative multihop transmission are derived when nodes are equipped with multiple antennas. Next, we formulate the problem of minimizing the transmit power for an outage-restricted equal power multihop network under the assumption of no instantaneous CSI knowledge at the transmitters. As another approach for managing the interferences induced by spatial-reused transmission, interference cancelation schemes are utilized in multihop networks with multiple-antenna nodes.

The remainder of this paper is organized as follows. In Section II, the system model and protocol description are given. The performance analysis of cooperative multihop transmission with spatial reuse is presented in Section III. In Section IV, two power control schemes are proposed. The interference cancelation techniques to remove the interferences induced by spatial-reuse transmissions are given in Section V. In Section VI, the overall performance of the system is presented for classical line networks. Finally, the conclusion is presented in Section VII.

II. System Model and Protocol Description

Consider a wireless communication network in which the source s intends to transmit its data to the destination d with the help of N cascaded intermediate nodes. Due to the broadcast nature of the wireless channel, some intermediate relays can overhear and retransmit the received packets. The channel between any two nodes in the network is assumed to be a Rayleigh fading. Analogues to [1], each transmission could either be a broadcast transmission where one node transmits the signal that is heard by multiple receivers, or be a cooperative transmission where multiple nodes concurrently transmit the signal to a single receiving node. Here, we adopt the cooperation protocol proposed in [21] which consists of $N+1$ transmission phases. We assume there is no CSI knowledge at transmitters and only statistical CSI is available at the transmitters. Thus, distributed space-time coded transmissions like codes proposed in [22] are the feasible choice to be employed for the cooperative transmission.

In general, cooperative transmission protocols have two major phases: non-cooperative and cooperative stages. Depending on the requirements, the non-cooperative phase may contain one or multiple steps. The next phases employ space-time cooperated transmission. As an example, Fig. 1 depicts a protocol employing distributed quasi-orthogonal space time code (D-QOST) with $M = 4$, where M is the number of cooperating nodes. The detailed description of cooperative multihop protocols, i.e., Broadcast-then-Cooperate, Multihop-then-Cooperate, and Full-Cooperation, is studied in [23]. For consistency, hereinafter, we consider the Multihop-then-Cooperate protocol illustrated in Fig. 1. However, the proposed procedure can be easily modified using two other protocols. Assuming the usage of full-rate distributed space-time codes, the number of cooperating nodes is equal to the transmitting packets. Hence, the source node intends to transmit M packets to the destination. The signals transmitted by the source terminal during the mth time slot of Phase 1 is denoted as $s_m(t)$, $m = 1,\ldots,M$ where t is the time index and is indicated as a group of M packets transmitted at a given time, and $\mathbb{E}\{s_m(t)\} = 0$ and $\mathbb{E}\{|s_m(t)|^2\} = 1$ for $m = 1,\ldots,M$. In Phase 1, the source transmits the information, and the signal received at the ith node in the first M time slots is given by

$$y_{i,m}(t) = \sqrt{P_{0,1}}h_{0,i}s_m(t) + v_{i,m}(t), \text{ for } m = 1,\ldots,M, \quad (1)$$

where $P_{0,1}$ is the average transmit power of the source symbol in the first phase, and $v_{i,m}$ denotes complex zero-mean white Gaussian noise with variance $\mathcal{N}_0$. The link coefficients from the jth node to the ith node $h_{j,i}$, $j = 0,1,\ldots,N$, $i = 1,2\ldots,N+1$, are complex Gaussian random variables with zero-mean and variances $\sigma^2_{j,i}$, where the $(N+1)$th node is the destination d. We assume coherence times of the channels are such that channel coefficients $h_{j,i}$ are not varying during M consecutive time slots. Note that $\sigma^2_{j,i} = (d_0/d_{j,i})^\delta$ is the path-loss coefficient, where $d_{j,i}$ is the distance between nodes j and i, δ is the path-loss exponent, which typically lies in the range of $2 \le \delta \le 6$, and d_0 depends on the operating frequency.

For the first $M-1$ phases, we repeat the non-cooperative transmission described above for the nth relay, $1 \le n < M-1$ to retransmit the source data. After initial stages, the cooperative transmission is utilized for routing the source packets to the destination. In contrast to [1] where transmitters are able to modify their phases, here, the *instantaneous CSI* is not known at the transmitter nodes. This assumption is realistic for most wireless systems. Hence, space-time coded cooperation is the appropriate choice to achieve the spatial diversity gain. In Phase n, $M \le n$, the previous M nodes transmit their signals concurrently toward the next node using an appropriate distributed space-time code.

To facilitate the simultaneous transmission of several packets in the network, the available bandwidth is reused among transmitters, with a minimum separation of K nodes between concurrently transmitting nodes. Fig. 2 shows a spatial-reused

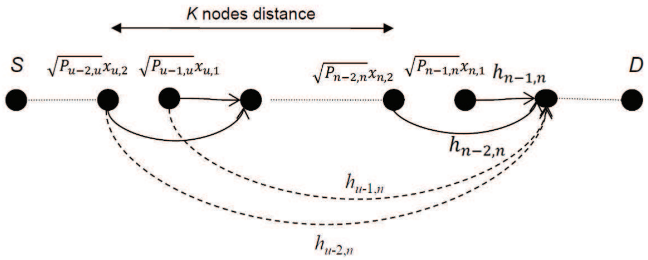

Fig. 2. Spatial-reused cooperative multihop network with $M=2$.

cooperative multihop network with $M=2$. Since in Phase $n \geq M$, M nodes transmit the intended data to the nth node, and by assuming half-duplex transmission, the minimum value of the spatially-reused factor K is $M+1$, and thus, $M+1 \leq K \leq N+1$. For the message detection, the nth node consider all received signals not coming from the M previous nodes as Gaussian interference. In this work, we treat the interference as the additive Gaussian noise. In the presence of inter-network interference from the spatial-reused nodes, for $n \geq M$ the received signal at the n-th receiving node can be represented as

$$y_{n,m}(t) = \sum_{m=1}^{M} \sqrt{P_{n-m,n}} h_{n-m,n} x_{n,m}(t) + \sum_{u \in \mathscr{U}_n} \sum_{m=1}^{M} \sqrt{P_{u-m,u}} h_{u-m,n} x_{u,m}(t-\tau) + v_{n,m}(t), \quad (2)$$

where $x_{n,m}(t)$ is the zero-mean space-time coded signal, normalized as $\mathbb{E}\{|x_{n,m}(t)|^2\} = 1$ during the whole packet transmission, and $P_{n-m,n}$, $m = 1, \ldots, M$, is the average transmit power of node $n-m$ during the mth time slot of Phase n. In (2), $\mathscr{U}_n$ denotes the set of nodes transmitting simultaneously with Nodes $n-m$, $m = 1, \ldots, M$, due to spatial reuse, i.e.,

$$\mathscr{U}_n = \{u \in \{1, 2, \ldots, N+1\} | u \neq n \text{ and } K \text{ divides } n-u\}, \quad (3)$$

and $\tau = \frac{n-u}{K}$. If there is the knowledge of forwarding channels at the nth node, the interference from the forwarding messages can be easily removed. The reason is that those messages have already detected in the nth node. Therefore, in this case, the set of interfering nodes in (3) can be modified as

$$\mathscr{U}_n' = \{u \in \{1, 2, \ldots, n-1\} | u \neq n \text{ and } K \text{ divides } n-u\}. \quad (4)$$

However, estimating the forwarding channels might not be practical due to increasing the signaling overhead. Thus, it is assumed that all hops use the total bandwidth of W, and we are interested in the reliable delivery of messages at a rate of R bits/second/Hertz by consuming the minimum total transmit power.

III. Performance Analysis of Multihop Transmission with Spatial Reused Space-Time Coded Cooperation

In the following, the outage probability $\rho_n^{\text{out}} \triangleq \Pr\{r_n < R\}$ of the nth receiving node at the nth hop in spatial-reused system is derived, which describes the probability that the transmit rate R is larger than the supported rate r_n. This probability depends on the fixed transmission parameters and the channel condition within the hops.

In the cooperative multihop transmission with spatial reuse factor of K, from (1) and (2), the instantaneous achieved rate at the nth hop becomes

$$r_n = \frac{1}{K} \log\left(1 + \frac{\sum_{m=1}^{M} P_{n-m,n} |h_{n-m,n}|^2}{\mathscr{N}_0 W + \sum_{u \in \mathscr{U}_n} \sum_{m=1}^{M} P_{u-m,u} |h_{u-m,n}|^2}\right), \quad (5)$$

where $P_{n-i,n} = 0$ for $n = 1, \ldots, M-1$, $i = 2, \ldots, M$.

A. Outage Probability

Here, we derive an exact closed-form expression for the outage probability at the nth receiving node in presence of interference from the multiple-antenna secondary BS. By defining $\gamma_{\text{th}} \triangleq 2^{RK} - 1$, the outage probability of the cooperative transmission can be given by

$$\rho_n^{\text{out}} = \Pr\left\{\frac{\sum_{m=1}^{M} P_{n-m,n} |h_{n-m,n}|^2}{\mathscr{N}_0 W + \sum_{u \in \mathscr{U}_n} \sum_{m=1}^{M} P_{u-m,u} |h_{u-m,n}|^2} < \gamma_{\text{th}}\right\}. \quad (6)$$

Thus, the receiver can reliably decode the source data whenever $r_n \geq R$. For decoding the message correctly, the outage probability must be less than a desired end-to-end outage probability $\rho_{\max}$.

Lemma *1 ([24]):* Considering a set of independent exponential random variables $\mathscr{X} = \{X_1, \ldots, X_M\}$ with mean of $\sigma_{x_m}^2$, $m = 1, \ldots, M$, the cumulative distribution function (CDF) of the summation of independent-not-identical exponentially distributed random variables, i.e., $X = \sum_{m=1}^{M} X_m$ is given by

$$\Pr\{X < x\} = \sum_{m=1}^{M} \alpha_m \left(1 - e^{\frac{-x}{\sigma_{x_m}^2}}\right), \quad (7)$$

where

$$\alpha_m = \prod_{\substack{j=1 \\ j \neq m}}^{M} \frac{\sigma_{x_m}^2}{\sigma_{x_m}^2 - \sigma_{x_j}^2}. \quad (8)$$

Using inductive reasoning, the following lemma can be obtained:

Lemma *2:* For α_m defined in (8), the following properties hold:

$$\sum_{m=1}^{M} \alpha_m = 1, \quad (9)$$

$$\sum_{m=1}^{M} \frac{\alpha_m}{\sigma_{x_m}^{2k}} = 0, \text{ for } k = 1, \ldots, M-1, \quad (10)$$

$$\sum_{m=1}^{M} \frac{\alpha_m}{\sigma_{x_m}^{2M}} = \frac{(-1)^{M+1}}{\prod_{m=1}^{M} \sigma_{x_m}^2}. \quad (11)$$

Proposition *1:* Given finite sets of independent random variables $\mathscr{X} = \{X_1, \ldots, X_M\}$ and $\mathscr{Y} = \{Y_1, \ldots, Y_Q\}$ with non-identical exponential distribution and mean of $\sigma_{x_m}^2$, $m = 1, \ldots, M$, and $\sigma_{y_q}^2$, $q = 1, \ldots, Q$, respectively, the CDF of $\text{SINR} = \frac{\sum_{m=1}^{M} X_m}{1 + \sum_{q=1}^{Q} Y_q}$ can be calculated as

$$\Pr\{\text{SINR} < \gamma\} = 1 - \sum_{m=1}^{M} \alpha_m e^{-\frac{\gamma}{\sigma_{x_m}^2}} \prod_{q=1}^{Q} \left(\frac{\sigma_{y_q}^2}{\sigma_{x_m}^2} \gamma + 1\right)^{-1}. \quad (12)$$

Proof: The proof is given in Appendix I. ■

From Proposition 1 and by defining $X_m = \frac{P_{n-m,n}|h_{n-m,n}|^2}{\mathcal{N}_0 W}$, $m = 1,\ldots,M$, $Y_q = \frac{P_{u-m,u}|h_{u-m,n}|^2}{\mathcal{N}_0 W}$, $q = 1,\ldots,Q$, and $Q = |\mathscr{U}_n|M$ where $|\mathscr{U}_n|$ denotes the cardinality of the set $\mathscr{U}_n$, the outage probability in (6) can be written as

$$\rho_n^{\text{out}} = \Pr\{\text{SINR} < \gamma_{\text{th}}\} = 1 - \sum_{m=1}^{M} \alpha_{m,n} e^{-\frac{\gamma_{\text{th}}\mathcal{N}_0 W}{P_{n-m,n}\sigma^2_{n-m,n}}} \times \prod_{u\in\mathscr{U}_n}\prod_{i=1}^{M}\left(\frac{P_{u-i,u}\sigma^2_{u-i,n}}{P_{n-m,n}\sigma^2_{n-m,n}}\gamma_{\text{th}}+1\right)^{-1}, \tag{13}$$

where

$$\alpha_{m,n} = \prod_{\substack{j=1\\ j\neq m}}^{M} \frac{P_{n-m,n}\sigma^2_{n-m,n}}{P_{n-m,n}\sigma^2_{n-m,n} - P_{n-j,n}\sigma^2_{n-j,n}}. \tag{14}$$

The outage probability ρ_n at the nth receiver is affected by all previous n nodes. An upper-bound expression for the outage probability at the destination, i.e., at the $(N+1)$th hop can be found as [23, Eq. (29)]

$$\rho_{\text{out}} \leq 1 - \prod_{\nu=0}^{N}\left(1-\rho^{\text{out}}_{N-\nu+1}\right)^{\Omega_M(\nu)}, \tag{15}$$

where $\Omega_M(\nu) = 1$, $0 \leq \nu < M$, which represent the first $M-1$ non-cooperative phases, and $\Omega_M(\nu) = \sum_{i=1}^{M}\Omega_M(\nu-i)$, $M \leq \nu \leq N$, describe next M-cooperative phases. Note that for the case of $M = 2$, $\{\Omega_2(\nu)\}$ is a Fibonacci sequence, i.e., $\Omega_2(\nu) = \Omega_2(\nu-1) + \Omega_2(\nu-2)$. In addition, for the extreme case of $M = N+1$, we have $\Omega_{M+1}(\nu) = 2^{\nu-1}$. In addition, when $M = 1$, i.e., in the non-cooperative multihop transmission scenario, we have $\Omega_1(\nu) = 1$, for $\nu = 0,\ldots,N$. It is important to note that assuming the equality in (15) implies that the outage at the destination happens even if one intermediate node experience an error. This guarantees that by using the power control strategies proposed in the next section, the outage probability QoS at the destination is satisfied. By assuming, $\rho_n^{\text{out}} = \rho_0$, $n = 1,\ldots,N+1$, to get an insight into the relationship between the end-to-end outage probability of $\rho_{\text{des}} \triangleq \rho_{N+1}$ and ρ_0, we have

$$\rho_{\text{des}} = 1 - \prod_{\nu=0}^{N}(1-\rho_0)^{\Omega_M(\nu)} = 1-(1-\rho_0)^{\sum_{\nu=0}^{N}\Omega_M(\nu)}. \tag{16}$$

Thus, the target outage probability at each hop ρ_0 can be represented in terms of the desired probability of error at the destination ρ_{des}.

Furthermore, assuming $\rho_{\text{out}} \ll 1$, the outage probability at the destination in (15) can be approximated as follows:

$$\rho_{\text{out}} \approx \sum_{\nu=0}^{N}\Omega_M(\nu)\,\rho^{\text{out}}_{N-\nu+1}. \tag{17}$$

Proposition *2:* In high SNR conditions, i.e., when $\text{SNR}_{n,m} \triangleq \frac{P_{n-m,n}\sigma^2_{n-m,n}}{\mathcal{N}_0 W} \gg 1$, and medium or low interference scenario due to spatial-reuse where interference terms is defined as $\text{INR}_{n,u,m} \triangleq \frac{P_{u-m,u}\sigma^2_{u-m,n}}{\mathcal{N}_0 W}$, the outage probability at the nth receiving node can be stated as

$$\rho_n^{\text{out}} \approx \frac{\gamma_{\text{th}}^M}{\prod_{m=1}^{M}\text{SNR}_{n,m}}\sum_{u\in\mathscr{U}_n}\sum_{m=1}^{M}\alpha'_{m,u,n}\sum_{i=0}^{M}\frac{\text{INR}^i_{n,u,m}}{(M-i)!}, \tag{18}$$

where $\alpha'_{m,u,n}$ is defined as

$$\alpha'_{m,u,n} = \prod_{\substack{i\in\mathscr{U}_n\\ (i,j)\neq(u,m)}}\prod_{j=1}^{M}\frac{P_{u-m,u}\sigma^2_{u-m,n}}{P_{u-m,u}\sigma^2_{u-m,n} - P_{i-j,i}\sigma^2_{i-j,n}}. \tag{19}$$

Proof: The proof is given in Appendix II. ■

From Proposition 2 and by using the definition of diversity order $G_d = \lim_{\text{SNR}\to\infty}\frac{-\log(\rho_n^{\text{out}})}{\log(\text{SNR})}$ [25, Eq. (1.19)], we have the following corollary:

Corollary *1:* In a spatial-reused multihop network with cooperation order of M, even in existence of inter-network interference due to spatial reuse, we can achieve the full diversity order of M.

Corollary *2:* In the interference-free conditions and the high SNR regime, the outage probability in (18) can be modified as

$$\rho_n^{\text{out}} \approx \frac{\gamma_{\text{th}}^M}{M!\prod_{m=1}^{M}\text{SNR}_{n,m}}. \tag{20}$$

From Proposition 1 and by using the facts that $e^{-x} \approx 1-x$ and $\frac{1}{1+x} \approx 1-x$, for $x \ll 1$, we have

Corollary *3:* In the high SNR regime, for a non-cooperative spatial-reused multihop transmission, i.e., when $M = 1$, the outage probability can be approximated as

$$\rho_n^{\text{out}} \approx \frac{\gamma_{\text{th}}}{\text{SNR}_{n,1}}\left(1+\sum_{u\in\mathscr{U}_n}\text{INR}_{n,u,1}\right). \tag{21}$$

If the interference due to spatial reuse is strong, the following corollary can be obtained from Proposition 2:

Corollary *4:* In the high SNR and high interference scenario, i.e., when $\text{SNR}_{n,m} \gg 1$ and $\text{INR}_{n,u,m} \gg 1$, the system becomes interference-limited due to an error floor, and the outage probability can be approximated as

$$\rho_n^{\text{out}} \approx 1 - \sum_{m=1}^{M}\prod_{\substack{j=1\\ j\neq m}}^{M}\frac{\text{SNR}_{n,m}}{\text{SNR}_{n,m}-\text{SNR}_{n,j}} \times \prod_{u\in\mathscr{U}_n}\prod_{i=1}^{M}\left(\frac{\text{INR}_{n,u,i}}{\text{SNR}_{n,m}}\gamma_{\text{th}}+1\right)^{-1}. \tag{22}$$

B. Extension to Multiple Antenna (MA) Case

In this subsection, we derive the close-form expressions for the outage probability of the cooperative multihop transmission when nodes are equipped with M_s antennas.

Lemma *3 ([24]):* Consider M sets of independent random variables $\mathscr{X}_m = \{X_{m,1},\ldots,X_{m,M_s}\}$, for $m = 1,\ldots,M$, with exponential distribution, where RVs in each set have identical mean of $\sigma^2_{x_m}$, $m = 1,\ldots,M$, while every two sets have distinct mean, i.e., $\sigma^2_{x_i} \neq \sigma^2_{x_j}$ for $i \neq j$. The CDF of the summation of independent-partly-not-identical exponentially distributed random variables, i.e., $X = \sum_{m=1}^{M}\sum_{i=1}^{M_s}X_{m,i}$ is given by

$$\Pr\{X<x\} = 1-\left[\prod_{m=1}^{M}\sigma_{x_m}^{-2M_s}\right]\sum_{m=1}^{M}\sum_{i=1}^{M_s}\frac{\Psi_{m,i}(-\sigma_{x_m}^{-2})x^{M_s-1}e^{\frac{-x}{\sigma^2_{x_m}}}}{(M_s-i)!(-1)!}, \tag{23}$$

where

$$\Psi_{m,i}(t) = -\frac{\partial^{i-1}}{\partial t^{i-1}} \left\{ \prod_{\substack{j=0 \\ j\neq m}}^{M} (\sigma_{x_j}^{-2} + t)^{-M_s} \right\}. \quad (24)$$

Proposition *3:* Consider a finite set of independent exponentially distributed random variables $\mathscr{X} = \{X_1, \ldots, X_M\}$ and $\mathscr{Y} = \{Y_1, \ldots, Y_Q\}$, where $X_m = [X_{m,1}, \ldots, X_{m,M_s}]$, $m = 1, \ldots, M$, and $Y_q = [Y_{q,1}, \ldots, Y_{q,M_s}]$, $q = 1, \ldots, Q$, are M_s dimensional vectors of i.i.d RVs with mean of $\sigma_{x_m}^2$, and $\sigma_{y_q}^2$, respectively. The CDF of

$$\mathrm{SINR}_{\mathrm{MA}} = \frac{\sum_{m=1}^{M} \sum_{i=1}^{M_s} X_{m,i}}{1 + \sum_{q=1}^{Q} \sum_{i=1}^{M_s} Y_{q,i}}$$

can be calculated as

$$\Pr\{\mathrm{SINR}_{\mathrm{MA}} < \gamma\} = 1 - \sum_{m=1}^{M} D_m \gamma^{M_s - 1} \sum_{k=0}^{\infty} V_k \times \sum_{i=0}^{M_s-1} \binom{M_s - 1}{i} \frac{(i + QM_s + k - 1)! e^{-\frac{\gamma}{\sigma_{x_m}^2}}}{\left(\frac{1}{\sigma_{x_m}^2} + \frac{1}{\beta_1}\right)^{i+QM_s+k}}, \quad (25)$$

where

$$D_m = \left[\prod_{n=1}^{M} \sigma_{x_n}^{-2M_s}\right] \sum_{i=1}^{M_s} \frac{\Psi_{m,i}(-\sigma_{x_m}^{-2})}{(M_s - l)!\,(i-1)!}, \quad (26)$$

$$V_k = \prod_{q=1}^{Q} \frac{\beta_1^{M_s}}{\sigma_{y_q}^{2M_s}} \sum_{k=0}^{\infty} \frac{\delta_k}{\beta_1^{QM_s+k} (QM_s + k - 1)!}. \quad (27)$$

Proof: The proof is given in Appendix III. ■

From Proposition 3, and by assuming equal transmit power across antennas at each of nodes, the outage probability at the n-th hop, i.e., ρ_n^{MA} is given in (25) where $\sigma_{x_m}^2 = \frac{P_{n-m,n} \sigma_{n-m,n}^2}{M_s \mathscr{N}_0 W}$ and $\sigma_{y_q}^2 = \frac{P_{u-m,u} \sigma_{u-m,n}^2}{M_s \mathscr{N}_0 W}$. Furthermore, the outage probability at the destination can be obtained via (15).

So far, the impact of spatial-reuse interference on the performance of cooperative multihop system is studied. In the subsequent sections, we introduce two approaches to improve the system performance, i.e., power control and interference cancelation.

IV. Power Allocation for Multihop Transmission with Interference

In this section, we derive the required power for the multihop transmission scheme discussed in Section II in order to achieve a certain rate R with a given outage probability QoS. In the following, two power allocation strategies are proposed.

A. Equal-Power Per-Hop Outage Constrained Power Allocation

Finding the optimal value of the transmit powers can be challenging due to the complexity of outage probability $\Pr\{r_n < R\}$ derived in (13) and (18). By assuming an equal power at every node, in what follows, a suboptimal power allocation strategy is proposed. In the case of interference-free transmission, as stated in [23, Theorem 1], the cooperative transmit power coefficients should be equal in each transmission phase, i.e., $P_{n-m,n} = P_n$, $n = 1, \ldots, N+1$. To get a more accurate result, we further assume equal transmission power in all phases to achieve a target outage probability QoS. Thus, assuming the equal transmit power, i.e., $P_{n-m,n} = P_{u-m,u} = P_0$, for $m = 1, \ldots, M$, $n = 1, \ldots, N+1$, and $u \in \mathscr{U}_n$, we have

$$\rho_n^{\mathrm{out}} = 1 - e^{-\frac{\gamma_{\mathrm{th}} \mathscr{N}_0 W}{P_0 \sigma_{n-1,n}^2}} \prod_{u \in \mathscr{U}_n} \prod_{i \in \mathscr{M}_u} \left(\frac{\sigma_{u-i,n}^2}{\sigma_{n-1,n}^2} \gamma_{\mathrm{th}} + 1 \right)^{-1}, \quad (28)$$

for $n = 1, \ldots, M-1$, where $\mathscr{M}_u = \{1\}$ if $u < M$, and $\mathscr{M}_u = \{1, 2, \ldots, M\}$, if $u \geq M$. For $n = M, \ldots, N+1$, the outage probability can be rewritten as

$$\rho_n^{\mathrm{out}} = 1 - \sum_{m=1}^{M} A_{m,n}\, e^{-\frac{\gamma_{\mathrm{th}} \mathscr{N}_0 W}{P_0 \sigma_{n-m,n}^2}}, \quad (29)$$

where

$$A_{m,n} = \prod_{\substack{j=1 \\ j\neq m}}^{M} \frac{\sigma_{n-m,n}^2}{\sigma_{n-m,n}^2 - \sigma_{n-j,n}^2} \prod_{u \in \mathscr{U}_n} \prod_{i \in \mathscr{M}_u} \left(\frac{\sigma_{u-i,n}^2}{\sigma_{n-m,n}^2} \gamma_{\mathrm{th}} + 1 \right)^{-1}. \quad (30)$$

Since ρ_n^{out} is a decreasing function of the power coefficient P_0 for $P_0 \geq 0$, to find the minimum value of the problem in P_0, the constraint $\rho_n^{\mathrm{out}} \leq \rho_n$ is turned into the equality. Thus, the positive root of $\rho_n^{\mathrm{out}} - \rho_n = 0$ should be calculated. Hence, from (28), for $n = 1, \ldots, M-1$, we have

$$P_n = \frac{-\gamma_{\mathrm{th}} \mathscr{N}_0 W \sigma_{n-1,n}^{-2}}{\ln(1 - \rho_n) + \sum_{u \in \mathscr{U}_n} \ln\left(\frac{\sigma_{u-1,n}^2}{\sigma_{n-1,n}^2} \gamma_{\mathrm{th}} + 1 \right)}. \quad (31)$$

For $n = M, \ldots, N+1$, and for a given initial value, P_n can be calculated from (29) using the following recursive equation:

$$P_n^{(t+1)} = \frac{-\gamma_{\mathrm{th}} \mathscr{N}_0 W \sigma_{n-1,n}^{-2}}{\ln\left[\frac{1-\rho_n}{A_{1,n}} - \sum_{i \in \mathscr{M}_u - \{1\}} \frac{A_{m,n}}{A_{1,n}} e^{-\frac{\gamma_{\mathrm{th}}}{P_n^{(t)} \sigma_{n-m,n}^2}} \right]}, \quad (32)$$

where $P_n^{(t)}$ is the updated version of the power coefficient in the t-th iteration. Since ρ_n^{out} is a decreasing function of P_n, to guarantee that $\rho_n^{\mathrm{out}} \leq \rho_n$ where ρ_n is a target outage probability per hop, we have

$$P_0 = \max\{P_n^*\}, \quad (33)$$

where P_n^* is the solution of (31) and the recursive equation in (32). Assuming a fixed per-hop outage target of $\rho_n = \rho_0$ and using (16), we can represent P_0 in terms of ene-to-end outage probability of ρ_{des} by replacing ρ_n with $\rho_0 = 1 - [1 - \rho_{\mathrm{des}}]^{\frac{1}{\sum_{v=0}^{N} \Omega_M(v)}}$ in (32).

Proposition *4:* In the spatial-reused multihop transmission, the minimum allowed target outage requirement at the destination is given by

$$\rho_{\mathrm{des}} \geq 1 - \left[\prod_{n=1}^{M-1} \prod_{u \in \mathscr{U}_n} \prod_{i \in \mathscr{M}_u} \left(\frac{\sigma_{u-i,n}^2}{\sigma_{n-1,n}^2} \gamma_{\mathrm{th}} + 1 \right)^{-1} \right] \times \prod_{n=M}^{N+1} \left(\sum_{m=1}^{M} A_{m,n} \right)^{\Omega_M(N-n+1)}. \quad (34)$$

Proof: The minimum amount of permissable target outage per hop can be obtained by putting $P_n \to \infty$ in (28) and (29) to get

$$\rho_n \geq 1 - \prod_{u \in \mathscr{U}_n} \prod_{i \in \mathscr{M}_u} \left(\frac{\sigma_{u-i,n}^2}{\sigma_{n-1,n}^2} \gamma_{\text{th}} + 1 \right)^{-1}, \tag{35}$$

for $n = M, \ldots, N+1$, and

$$\rho_n \geq 1 - \sum_{m=1}^{M} A_{m,n}, \text{ for } n = M, \ldots, N+1. \tag{36}$$

Combining (15), (35), and (36), the minimum feasible outage probability QoS at the destination is obtained as (34). ■

In addition, for a given desired outage probability ρ_{des} at the destination, one can find the minimum spatial-reused factor, i.e., nodes distance K, using Proposition 3. Moreover, it can be observed from (9), (34), and (36) that when there is no interference, we have $\rho_{\text{des}} \geq 0$, and thus, there is no limitation in choosing ρ_{des}.

For the case of non-cooperative multihop transmission, i.e., when $M = 1$, the closed-form solution for P_0 is given by the following proposition:

Proposition *5:* Assuming the equal power transmission from all nodes, the minimum transmit power P_0^* per node to achieve a per-hop outage probability of ρ_n in a non-cooperative spatial-reused multihop system over Rayleigh fading channels can be expressed as

$$P_0^* = \max_n \left\{ \frac{\gamma_{\text{th}} \mathscr{N}_0 W \sigma_{n-1,n}^{-2}}{\rho_n - \gamma_{\text{th}} \sum_{u \in \mathscr{U}_n} \frac{\sigma_{u-1,n}^2}{\sigma_{n-1,n}^2}} \right\}. \tag{37}$$

Proof: From the approximation given in Corollary 3, which is actually an upper-bound, and by the fact that $P_n = P_0$, for $n = 1, \ldots, N+1$, we have

$$\rho_n^{\text{out}} \leq \frac{\gamma_{\text{th}} \mathscr{N}_0 W}{P_n \sigma_{n-m,n}^2} + \gamma_{\text{th}} \sum_{u \in \mathscr{U}_n} \frac{\sigma_{u-1,n}^2}{\sigma_{n-1,n}^2}. \tag{38}$$

Then, combining (33) and (38), the result in (37) can be yielded. ■

Therefore, for the case of Multihop-then-Cooperate protocol, the total transmit power for transmitting a packet is given by

$$\begin{aligned} P_T &= \sum_{n=1}^{N+1} \mathscr{C}(\text{Tx}_n, n) = \sum_{n=1}^{M-1} P_{n-1,n} + \sum_{n=M}^{N+1} \sum_{m=1}^{M} P_{n-m,n} \\ &= (3M + MN - M^2 - 1) P_0^*. \end{aligned} \tag{39}$$

Moreover, P_0^* in Proposition 5 can be written in terms of the desired outage probability at the destination, i.e., ρ_{des}. For instance, an upper-bound for P_0 can be obtained from (37), by replacing ρ_n with $1 - (1 - \rho_{\text{des}})^{1/(\sum_{v=0}^{N} \Omega_M(v))}$.

B. Power Allocation with End-to-End Outage Constraint

The power allocation proposed in Subsection IV-A is not optimal in terms of minimizing the total transmit power given an end-to-end outage probability constraint ρ_{des}. Moreover, in the previous subsections, we introduced the per-hop outage probability ρ_0 and ρ_n. If the intermediate relays do not intend to use the source's data, and act only as passive nodes to relay source's messages, the outage probability constraint for each hop is not required. Therefore, in this subsection, we propose a centralized power allocation schemes to achieve the rate R with an end-to- end outage probability constraint ρ_{des} at the destination. The proposed power control in this subsection is optimal in the sense of minimizing the transmit power given a constraint ρ_{des}.

1) Non-Cooperative Multihop Link Cost: First, we investigate non-cooperative transmit powers $P_{n-1,n}$ to satisfy the target rate R with a target outage probability of ρ_{des} at the destination. We consider that the receiver can correctly decode the source data whenever $P_{n-i,n} |h_{n-i,n}|^2 \geq \gamma_{\text{th}}$. Hence, in $1 - \rho_{\text{des}}$ of the total transmissions, we have a reliable detection of symbols. From (15) and (20), the outage probability at the destination becomes

$$\begin{aligned} \rho_{\text{out}} &\approx 1 - \prod_{n=1}^{N+1} \left[1 - \frac{\gamma_{\text{th}}}{\text{SNR}_{n,1}} \left(1 + \sum_{u \in \mathscr{U}_n} \text{INR}_{n,u,1} \right) \right] \\ &\leq \sum_{n=1}^{N+1} \frac{\gamma_{\text{th}}}{\text{SNR}_{n,1}} \left(1 + \sum_{u \in \mathscr{U}_n} \text{INR}_{n,u,1} \right) \\ &= \sum_{n=1}^{N+1} \hat{\rho}_n^{\text{out}} \triangleq f(P_{0,1}, \ldots, P_{N,N+1}), \end{aligned} \tag{40}$$

where $\hat{\rho}_n^{\text{out}} = \frac{\gamma_{\text{th}}}{P_{n-1,n} \sigma_{n-1,n}^2} \left[\mathscr{N}_0 W + \sum_{u \in \mathscr{U}_n} P_{u-1,u} \sigma_{u-1,n}^2 \right]$.

Now, we formulate the problem of power allocation in the non-cooperative multihop networks with the acceptable outage probability of ρ_{des} at the destination. The link cost or total transmitted power for all $(N+1)$ phases becomes $\mathscr{C} = \sum_{n=1}^{N+1} P_{n-1,n}$. Therefore, the power allocation problem, which has a required outage probability constraint on the destination node, can be formulated as

$$\begin{aligned} &\min \sum_{n=1}^{N+1} P_{n-1,n}, \\ &\text{s.t. } f(P_{0,1}, \ldots, P_{N,N+1}) \leq \rho_{\text{des}}, \\ &\quad P_{n-1,n} \geq 0, \text{ for } n = 1, \ldots, N+1. \end{aligned} \tag{41}$$

Therefore, the required transmit power can be calculated in the following theorem:

Proposition *6:* The optimal power allocation values $P_{k-1,k}^*$ in the optimization problem (41) can be obtained recursively from the following equations:

$$P_{k-1,k} = \frac{\lambda \rho_k^{\text{out}}}{1 + \sum_{\substack{n=1, n \neq k \\ k \in \mathscr{U}_n}}^{N+1} \frac{\gamma_{\text{th}}}{P_{n-1,n} \sigma_{n-1,n}^2} \sigma_{k-1,n}^2}, \tag{42}$$

for $k = 1, \ldots, N+1$, where

$$\lambda = \frac{\sum_{n=1}^{N+1} P_{n-1,n}}{\rho_{\text{des}} - \sum_{i=1}^{N+1} P_{i-1,i} \sum_{\substack{n=1, n \neq i \\ i \in \mathscr{U}_n}}^{N+1} \frac{\gamma_{\text{th}}}{P_{n-1,n} \sigma_{n-1,n}^2} \sigma_{i-1,n}^2}. \tag{43}$$

Proof: The proof is given in Appendix IV. ■

Hence, the non-cooperative multihop link cost is given by

$$P_T(\text{non-coop}) = \sum_{n=1}^{N+1} P_{n-1,n}^*. \tag{44}$$

2) Cooperative Multihop Link Cost: Here, our objective is to find the minimum power allocation required for the cooperative transmission in order to achieve certain rate R with the successful reception of source's data at the destination. For decoding the message reliably, the outage probability at the destination must be less than the desired end-to-end outage probability ρ_{des}.

As stated in Section II, the source node transmits M symbols with the power $P_{0,1}$ during the first phase. In Phase n, $n = M, \ldots, N+1$, a set of M nodes $\mathrm{Tx}_n = \{\mathrm{tx}_{n,1}, \ldots, \mathrm{tx}_{n,M}\}$ cooperate to transmit information of the source to a *single* receiver node rx_n, as stated in (2). Therefore, the total transmission power in all phases becomes $P_T = \sum_{n=1}^{M-1} P_{n-1,n} + \sum_{n=M}^{N+1}\sum_{i=1}^{M} P_{n-i,n}$, such that the outage probability at the destination becomes less than the target value ρ_{des}.

From (17), the outage probability at the destination can be approximated as $\rho_{\mathrm{out}} \approx \sum_{\nu=0}^{N} \Omega_M(\nu)\, \rho_{N-\nu+1}^{\mathrm{out}} \triangleq \hat{\rho}_{\mathrm{out}}$. With a derivation similar to [26], it is straightforward to show that the approximated form (17) serves as an upper bound for the exact outage probability, i.e., $\rho_{\mathrm{out}} \leq \hat{\rho}_{\mathrm{out}}$. Thus, if $\hat{\rho}_{\mathrm{out}}$ is considered for distributing the power within the multihop system, the applied end-to-end probability constraint is more stringent. Note that the approximation in (17) is an upper-bound on the outage probability, and thus, is reliable to be used for all SNR conditions (low, medium, and high SNRs). Since the required outage probabilities at the destination ρ_{des} usually have small values, the corresponding required SNRs are high. Therefore, the power allocation problem, which has a required outage probability constraint on the receiving node, can be formulated as

$$\begin{aligned} &\min \sum_{n=1}^{M-1} P_{n-1,n} + \sum_{n=M}^{N+1}\sum_{i=1}^{M} P_{n-i,n}, \\ &\text{s.t.} \sum_{\nu=0}^{N} \Omega_M(\nu)\, \rho_{N-\nu+1}^{\mathrm{out}} \leq \rho_{\mathrm{des}}, P_{n-i,n} \geq 0, \text{ for } i = 1, \ldots, M. \end{aligned} \tag{45}$$

Finding the optimal solution of the transmit powers in (45) is complicated due to the complexity of outage probability ρ_n^{out} derived in (13). As a special case, we consider the interference-free scenario. The centralized power allocation for two-nodes cooperation is studied in [2]. Here, we extend it for a network with arbitrary number of cooperating nodes. Note that the following analysis is also valid for a network under interferences if we treat interference as noise.

From $1 - e^{-x} \leq x$, Corollary 2, and (17), an upper-bound for ρ_{out} can be obtained as

$$\rho_{\mathrm{out}} \approx \sum_{n=1}^{M-1} \frac{\gamma_{\mathrm{th}} \Omega_M(N-n+1)}{\sigma_{n-1,n}^2 P_{n-1,n}} + \sum_{n=M}^{N+1} \frac{\gamma_{\mathrm{th}}^M\, \Omega_M(N-n+1)}{M! \prod_{i=1}^{M} \sigma_{n-i,n}^2 P_{n-i,n}}. \tag{46}$$

Thus, for the case of interference-free centralized end-to-end outage constrained link cost formulation, we modify the outage restricted minimum power allocation problem of (45) as

$$\begin{aligned} &\min \sum_{n=1}^{M-1} P_{n-1,n} + \sum_{n=M}^{N+1}\sum_{i=1}^{M} P_{n-i,n}, \\ &\text{s.t.} \sum_{n=1}^{M-1} \frac{\gamma_{\mathrm{th}} \Omega_M(N-n+1)}{\sigma_{n-1,n}^2 P_{n-1,n}} + \sum_{n=M}^{N+1} \frac{\gamma_{\mathrm{th}}^M\, \Omega_M(N-n+1)}{M! \prod_{i=1}^{M} \sigma_{n-i,n}^2 P_{n-i,n}} \leq \rho_{\mathrm{des}}, \\ &\quad P_{n-i,n} \geq 0, \text{ for } i = 1, \ldots, M. \end{aligned} \tag{47}$$

Due to the symmetry between $P_{n-i,n}$, for $n = M, \ldots, N+1$, $i = 1, \ldots, M$, in the objective and constraint function in (47), it follows that $P_{n-i,n} = P_{n-1,n}$, $n = M, \ldots, N+1$, $i = 1, \ldots, M$. Therefore, the optimization problem in (47) is equivalent to

$$\begin{aligned} &\min \sum_{n=1}^{M-1} P_{n-1,n} + \sum_{n=M}^{N+1} M P_{n-1,n} \\ &\text{s.t.} \sum_{n=1}^{M-1} \frac{\gamma_{\mathrm{th}} \Omega_M(N-n+1)}{\sigma_{n-1,n}^2 P_{n-1,n}} + \sum_{n=M}^{N+1} \frac{\gamma_{\mathrm{th}}^M\, \Omega_M(N-n+1)}{M! P_{n-1,n}^M \prod_{i=1}^{M} \sigma_{n-i,n}^2} \leq \rho_{\mathrm{des}}, \\ &\quad P_{n-1,n} \geq 0. \end{aligned} \tag{48}$$

The outage constraint in (48) is a *posynomial* function [27], which is a convex function. Hence, since the objective function and the constraints are convex, the optimal power allocation values $P_{n-1,n}$ in the optimization problem (48) are unique.

From the Lagrangian (61) and the Kuhn-Tucker condition, the following set of equations can be found as

$$\begin{aligned} P_{n-1,n} &= \sqrt{\lambda \frac{\gamma_{\mathrm{th}} \Omega_M(N-n+1)}{\sigma_{n-1,n}^2}}, \text{ for } n = 1, \ldots, M-1, \\ P_{n-1,n} &= \sqrt[M+1]{\lambda \frac{\gamma_{\mathrm{th}}^M \Omega_M(N-n+1)}{M! \prod_{i=1}^{M} \sigma_{n-i,n}^2}}, \text{ for } n = M, \ldots, N+1. \end{aligned} \tag{49}$$

Since the strong duality condition [27, Eq. (5.48)] holds for convex optimization problems, the constraint in (48) is satisfied with equality:

$$\sum_{n=1}^{M-1} \frac{\gamma_{\mathrm{th}} \Omega_M(N-n+1)}{\sigma_{n-1,n}^2 P_{n-1,n}} + \sum_{n=M}^{N+1} \frac{\gamma_{\mathrm{th}}^M\, \Omega_M(N-n+1)}{M! P_{n-1,n}^M \prod_{i=1}^{M} \sigma_{n-i,n}^2} = \rho_{\mathrm{des}}. \tag{50}$$

Combining (49) and (50), we can find the optimal value of power coefficients $P_{n-1,n}$, $n = 1, \ldots, N+1$. By defining $a = \sum_{n=2}^{N+1} \frac{\sqrt{\gamma_{\mathrm{th}} \Omega_M(N-n+1)}}{\sigma_{n-1,n}}$, $b = \sqrt[M+1]{\frac{\gamma_{\mathrm{th}}^M \Omega_M(N-n+1)}{M! P_{n-1,n}^M \prod_{i=1}^{M} \sigma_{n-i,n}^2}}$, and $x = \lambda^{\frac{1}{2(M+1)}}$, we can find the optimal value of λ by solving $a x^{M+1} + b x^{2M} = \rho_{\mathrm{des}}$.

V. Interference Management in Multihop Transmission with Spatial-Reuse Interference

In this section, interference cancelation is employed to improve the performance of spatial-reused multihop systems.

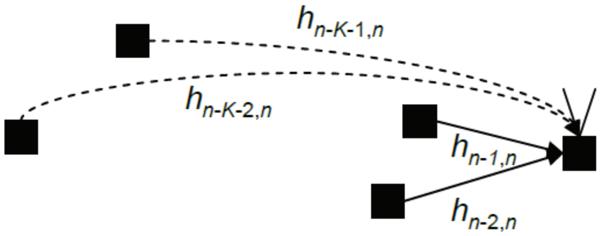

Fig. 3. Wireless space-timed coded multihop network with one interference stream due to spatial reused from previous nodes.

A. Interference Cancelation in Noncooperative Multihop Transmission with Interference

Let us start with the noncooprative transmission with concurrent signal transmission of nodes which are separated by K nodes. If we restrict the interference cancelation to two adjacent nodes, each node need to have *two antennas*. Assume that interfering packets s_3 and s_1 are transmitted from $n-K-1$ and $n+K-1$ nodes, and the desired packet s_2 is transmitted from the $(n-1)$th node. Assuming the knowledge of local channels are available at the nth node, the interference from $(n+K-1)$th node is simply removed (since in the previous hops nth node already detected the symbol s_1). Therefore, nodes equipped with two antennas can completely remove the interference caused by the $(n-K-1)$th node. We have two independent equations received by two antennas, and thus, the desired packet s_2 and the interfering packet s_3 are detected. This problem is actually equivalent to multiple access channel. The channel linearly combines the two packets. Hence, the two-antenna receiver can detect packets reliably.

Extending the procedure given above to interference cancelation for m interfering nodes is straightforward. Suppose there are m_1 and m_2 backward and forward interfering nodes, respectively, i.e., $m = m_1 + m_2$. We need to have $m_1 + 1$ antennas at each intermediate node. In this case, given the independence of channels, there would be $m_1 + 1$ independent equations and $m_1 + 1$ variables including the desired packet. In other words, the channel linearly combines $m_1 + 1$ packets (i.e., it linearly combines every $m_1 + 1$ digital samples of the packets). Hence, an $(m_1 + 1)$-antenna receiver can cancel the interference to recover the desired packet.

B. Interference Cancelation in Cooperative Multihop Transmission with Interference: Linear Processing

Consider the cooperative routing scenario with the simultaneous transmission of packets from nodes with the spatial separation of K nodes. In Section IV, the interference caused by spatial reused scheme is treated as noise. Here, we propose an interference cancelation technique for increasing the performance of cooperative routing in multihop networks with interference. For simplicity, we restrict the interference cancelation to two adjacent nodes. We assume that each node has channel state information (CSI) of local nodes and is able to remove the interferences from forward nodes. Thus, the interference cancelation problem only deals with the interference caused by

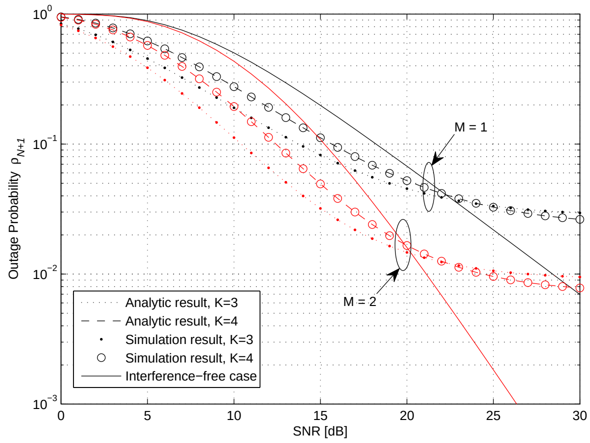

Fig. 4. The outage probability curves versus the transmit SNR in a wireless multihop network with $N = 5$ for non-cooperative ($M = 1$) and cooperative ($M = 2$) cases, different spatial reuse factors, and $R = \frac{1}{2}$ bits/sec/Hz.

backward nodes. Assume that s_1 and s_2 are transmitted from the $(n-K-2)$th and $(n-K-1)$th nodes using the Alamouti code, and the desired packets s_3 and s_4 are transmitted from the $(n-2)$th and $(n-1)$th nodes, respectively (see Fig. 3). The received signal at the nth receiving node in Phase n can be expressed as

$$\check{y}_n = \check{H}_n \check{\Lambda}_n s + \check{v}_n, \tag{51}$$

where $\check{y}_n$ and $\check{v}_n$ are 4×1 extended vector of the received signal and noise at the nth node equipped with two receiving antennas. The first and second two components of the received vector are corresponding to the received signals at the first and second antennas, respectively. The transmit vector and power allocation matrix in (51) are represented by $s = [s_1, s_2, s_3, s_4]^T$ and $\check{\Lambda}_n = \operatorname{diag}[P_{n-K-2,n-K}, P_{n-K-1,n-K}, P_{n-2,n}, P_{n-1,n}]$, respectively. The equivalent channel matrix is given by

$$\check{H}_n = \begin{bmatrix} h^{(1)}_{n-K-2,n} & h^{(1)}_{n-K-1,n} & h^{(1)}_{n-2,n} & h^{(1)}_{n-1,n} \\ h^{*(1)}_{n-K-1,n} & -h^{*(1)}_{n-K-2,n} & h^{*(1)}_{n-1,n} & -h^{*(1)}_{n-2,n} \\ h^{(2)}_{n-K-2,n} & h^{(2)}_{n-K-1,n} & h^{(2)}_{n-2,n} & h^{(2)}_{n-1,n} \\ h^{*(2)}_{n-K-1,n} & -h^{*(2)}_{n-K-2,n} & h^{*(2)}_{n-1,n} & -h^{*(2)}_{n-2,n} \end{bmatrix}, \tag{52}$$

where superscripts $^{(1)}$ and $^{(2)}$ refer to the first and second receiving antennas, respectively. Assuming $\check{H}_n^h \check{H}_n$, where $(\cdot)^h$ is conjugate transpose operation, is a full-rank matrix, we can successfully detect the desired packets s_3 and s_4. Therefore, the traditional MIMO interference cancelation techniques – or multiple access channels interference cancelation – can be employed. For example, one can use zero-force (ZF), minimum mean square error (MMSE), maximum likelihood (ML), or successive interference cancelation (SIC) techniques. For the case of nonlinear detection techniques like SIC, single-antenna nodes can be employed.

VI. Numerical Analysis

In this section, numerical results are provided to analyze the performance of the the proposed spatial-reused cooperative multihop scheme. A regular line topology is considered where

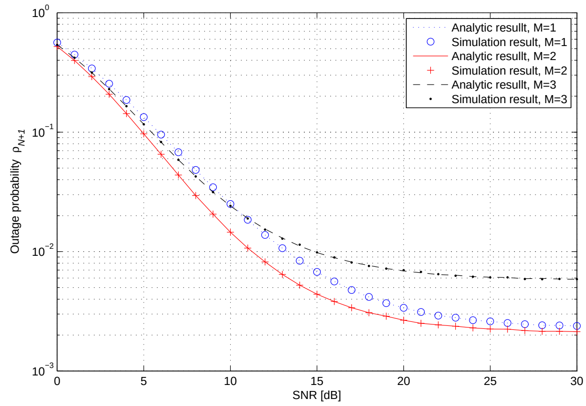

Fig. 5. The outage probability curves versus the transmit SNR in a wireless multihop network with multiple-antenna nodes of $M_s = 2$, $K = 3$, $N = 5$, $R = \frac{1}{2}$ bits/sec/Hz, and for non-cooperative ($M = 1$) and cooperative ($M = 2, 3$) cases.

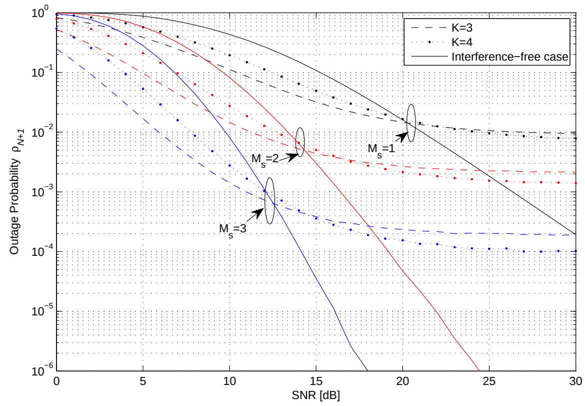

Fig. 6. The outage probability curves versus the transmit SNR in a wireless multihop network with different antenna numbers, different spatial reuse factors, $M = 2$, $N = 5$, and $R = \frac{1}{2}$ bits/sec/Hz.

nodes are located at *unit* distance from each other on a straight line. The optimal non-cooperative transmission in this network is to send the signal to the next closest node in the direction of the destination. Assume that rate R is $\frac{1}{2}$, bandwidth W is normalized to 1, the path-loss exponent is assumed to be 3, and the number of intermediate relay nodes are $N = 5$.

In Fig. 4, we compare the outage probability curves of the spatial-reused multihop transmission with respect to the interference-free multihop scenario. The depicted curves are outage probabilities at the last transmission phase, i.e., ρ_{N+1}, and the non-cooperative ($M = 1$) and cooperative ($M = 2$) cases with different spatial reuse factors ($K = 3, 4$) were compared with interference-free case. As it can be seen, in low and medium SNR regimes, spatial-reused multihop transmission outperforms the interference-free case. For instance, for the cooperative transmission case, when the outage probability of 10^{-1} is required at each step, using the spatial-reused scheme with $K = 3$, around 5 dB saving in transmit power is achievable compared to the interference-free case. However, in high SNR conditions, one can observe that the interference-free transmission performs better than spatial-reused schemes. Since higher K means lower concurrent transmissions, and thus, lower interferences, as K increases, curves get closer to the interference-free case. Furthermore, Fig. 4 confirms the correctness of our analytical results derived in (13), since the curves are exactly match the simulations results.

Fig. 5 and Fig. 6 consider a network with multiple-antenna nodes as discussed in Subsection III-B. The depicted curves in Fig. 5 are outage probabilities corresponding to a wireless spatial-reused multihop network with multiple-antenna nodes of $M_s = 2$, $K = 3$, and for non-cooperative ($M = 1$) and cooperative ($M = 2, 3$) cases. It can be seen that the analytical results obtained in Proposition 3 are confirmed by simulations. Moreover, it shown that a network with $M = 2$ outperforms a non-cooperative network and a network with $M = 3$. Hence, increasing the number of cooperating nodes is not always beneficial for the system performance. Similar to MIMO systems, the spatial diversity is beneficial for high SNR scenarios. However, in low SNR scenarios, the antenna selection or

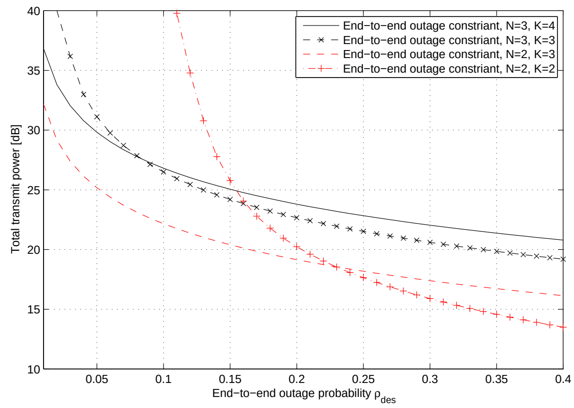

Fig. 7. The comparison of power allocation schemes studied in Subsection IV-B in terms of total transmit power versus the end-to-end outage probability ρ_{dest} in a wireless multihop network with different spatial reuse factors and $R = \frac{1}{2}$ bits/sec/Hz.

transmission from a single antenna outperforms the space-time coding (see, e.g., [25, p. 105]. In [28], it is also shown that the Alamaouti scheme works poorly compared to optimal coding in low SNR scenarios. Similar phenomenon can be happened in cooperative systems (see, e.g., [29]). In Fig. 6, we compare the outage probability curves versus transmit SNR by changing the number of antennas and spatial-reuse factors when $M = 2$. It can be observed that by adding more antennas, the system performs better in all SNR regimes.

In Fig. 7 and Fig. 8, we compare different power allocation schemes studied in Section IV in terms of total transmit power versus the end-to-end outage probability ρ_{dest} in a wireless multihop network with $N = 2, 3$ relays and $R = \frac{1}{2}$ bits/sec/Hz. It can be seen from Fig. 7 that as we increase the end-to-end outage probability constraint at the destination, spatial-reused case outperforms the non-spatial-reused case, i.e., $K = N + 1$ in term of energy consumption, when the power allocation introduced in Subsection IV-B is employed. For the effect of cooperation factor, M, it can be seen from Fig. 8 that the cooperative case ($M = 2$) leads to a better performance in term

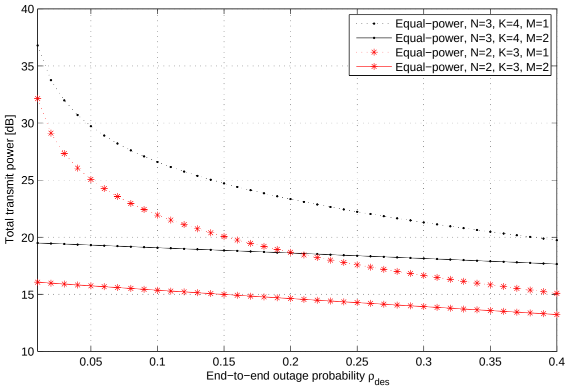

Fig. 8. The comparison of power allocation schemes studied in Subsection IV-A in terms of total transmit power versus the end-to-end outage probability ρ_{dest} in a wireless multihop network for non-cooperative ($M=1$) and cooperative ($M=2$) cases with different spatial reuse factors, and $R=\frac{1}{2}$ bits/sec/Hz.

of the consumed power compared to the non-cooperative case ($M=1$).

Finally, we summarize some key results to show the impact of parameters like K, M, and M_s in different settings studied above. For the impact of K, from Fig. 4 and 7, it is shown that the spatially-reused cooperative multihop transmission outperforms the non-spatial reused case in low and and medium SNRs, or equivalently, in high outage probability conditions. From Fig. 4, 5, and 7, it is observed that cooperative multihop transmission with $M=2$ outperforms the non-cooperative case in all SNR scenarios. In addition, the spatial reused cooperative multihop transmission with multiple antennas outperforms the single-antenna case in all SNR scenarios.

VII. Conclusion

In this paper, we have shown that by using the spatial-reused concurrent packet transmission, a higher spectral efficiency in wireless multihop networks in low or medium SNR conditions is achievable for a fixed transmission power. Alternatively, it is shown that by using the spatial-reused concurrent packet transmission, a higher energy efficiency in wireless multihop networks in low or medium SNR conditions is achievable for the fixed data rate and outage probability. We analyzed the performance of the spatially-reused cooperative multihop transmission. Then, the analysis is extended to calculate the outage probability of the system with multiple antenna nodes. Moreover, we have formulated the problem of finding the minimum energy cooperative transmission for a wireless network under Rayleigh fading. We have proposed a spatial-reused cooperative multihop routing for the purpose of energy savings, constrained on a required outage probability at the destination. The calculated power allocations are independent of instantaneous channel variation, and thus, can be used in practical wireless systems. Finally, interference cancelation schemes have been used to improve the performance of spatial-reused multihop systems for both cases of non-cooperative and cooperative transmissions.

Appendix I
Proof of Proposition 1

The PDF of Y_q is given as $p_q(y_q)=\frac{e^{-\frac{y}{\sigma^2_{y_q}}}}{\sigma^2_{y_q}}$. Moreover, the CDF of $X=\sum_{m=1}^{M}X_m$ is calculated in Lemma 1. By marginalizing over the independent random variables Y_q, the CDF of SINR can be calculated as

$$\begin{aligned}
&P\{\text{SINR}<\gamma\}\\
&=\int_{0;Q-\text{fold}}^{\infty}\Pr\left\{X<\gamma+\gamma\sum_{q=1}^{Q}y_q\right\}\prod_{q=1}^{Q}p_q(y_q)\,dy_q\\
&=\sum_{m=1}^{M}\alpha_m\int_{0;Q-\text{fold}}^{\infty}\left(1-e^{-\frac{\gamma(1+\sum_{q=1}^{Q}y_q)}{\sigma^2_{x_m}}}\right)\prod_{q=1}^{Q}p_q(y_q)\,dy_q\\
&=1-\sum_{m=1}^{M}\alpha_m e^{-\frac{\gamma}{\sigma^2_{x_m}}}\prod_{q=1}^{Q}\int_0^{\infty}e^{-y_q\left(\frac{\gamma}{\sigma^2_{x_m}}+\frac{1}{\sigma^2_{y_q}}\right)}\frac{dy_q}{\sigma^2_{y_q}},
\end{aligned}\tag{53}$$

where in the third equality, we used the first property of Lemma 2 in (9). Thus, the closed-form solution for integral in (53) is obtained as (12).

Appendix II
Proof of Proposition 2

We express the CDF of $X=\sum_{m=1}^{M}X_m$ in Lemma 1 in terms of its Taylor series as

$$\Pr\{X<x\}=\sum_{m=1}^{M}\alpha_m\sum_{k=1}^{\infty}\frac{-1}{k!}\left(\frac{-x}{\sigma^2_{x_m}}\right)^k. \tag{54}$$

In addition, $Y=\sum_{q=1}^{Q}Y_q$, where Y_q is defined in Lemma 1, has a distribution similar to X with different parameters, and its PDF can be represented as

$$p_y(y)=\sum_{q=1}^{Q}\frac{\alpha'_q}{\sigma^2_{y_q}}e^{-\frac{y}{\sigma^2_{y_q}}}, \tag{55}$$

where $\alpha'_q=\prod_{\substack{j=1\\ j\neq q}}^{Q}\frac{\sigma^2_{y_q}}{\sigma^2_{y_q}-\sigma^2_{y_j}}$. By marginalizing over the random variable Y and using (54), the integral in (53) can be rewritten as

$$\begin{aligned}
\Pr\{\text{SINR}<\gamma\}&=\int_0^{\infty}\Pr\{X<\gamma(1+y)\}\,p_y(y)\,dy\\
&=\int_0^{\infty}\sum_{m=1}^{M}\alpha_m\sum_{k=1}^{\infty}\frac{-1}{k!}\left(\frac{-\gamma(1+y)}{\sigma^2_{x_m}}\right)^k p_y(y)\,dy\\
&=\sum_{k=1}^{\infty}\Psi_k\sum_{m=1}^{M}\frac{\alpha_m}{\sigma^{2k}_{x_m}},
\end{aligned}\tag{56}$$

where Ψ_k is defined as

$$\Psi_k=\int_0^{\infty}\frac{(-1)^{k+1}\gamma^k(1+y)^k}{k!}p_y(y)\,dy. \tag{57}$$

Now, by replacing $p_y(y)$ from (55) in (57), we have

$$\begin{aligned}\Psi_k &= \int_0^\infty \frac{(-1)^{k+1}\gamma^k(1+y)^k}{k!}\sum_{q=1}^{Q}\frac{\alpha'_q}{\sigma^2_{y_q}}e^{-\frac{y}{\sigma^2_{y_q}}}\,dy\\ &= \frac{(-1)^{k+1}\gamma^k}{k!}\sum_{q=1}^{Q}\frac{\alpha'_q}{\sigma^2_{y_q}}\int_0^\infty (1+y)^k e^{-\frac{y}{\sigma^2_{y_q}}}\,dy\\ &= \frac{(-1)^{k+1}\gamma^k}{k!}\sum_{q=1}^{Q}\frac{\alpha'_q}{\sigma^2_{y_q}}\int_0^\infty \sum_{i=0}^{k}\binom{k}{i} y^i e^{-\frac{y}{\sigma^2_{y_q}}}\,dy\\ &= (-1)^{k+1}\gamma^k\sum_{q=1}^{Q}\alpha'_q\sum_{i=0}^{k}\frac{\sigma^{2i}_{y_q}}{(k-i)!}, \end{aligned} \tag{58}$$

where in the third equality, the binomial series expansion of $(1+y)^k$ is used. Combining (56) in (58) and the closed-form solution for the integral is obtained.

Then, by using the second property of Lemma 2, i.e., (10), the first $M-1$ terms in (56) becomes zero, and the outage probability is simplified as

$$\Pr\{\text{SINR} < \gamma\} = \sum_{k=M}^{\infty}\Psi_k\sum_{m=1}^{M}\frac{\alpha_m}{\sigma^{2k}_{x_m}}. \tag{59}$$

Finally, by the fact that $\sigma^2_{x_m} \gg 1$ is equivalent to $\text{SNR}_{n,m} \gg 1$, we can ignore higher order terms, and thus, we have $\Pr\{\text{SINR} < \gamma\} \approx \Psi_M\sum_{m=1}^{M}\frac{\alpha_m}{\sigma^{2M}_{x_m}}$. Using (11), the outage probability can be further simplified as

$$\Pr\{\text{SINR} < \gamma\} \approx \Psi_M\frac{(-1)^{M+1}}{\prod_{m=1}^{M}\sigma^2_{x_m}}.$$

Hence, the result in (18) is obtained.

Appendix III
Proof of Proposition 3

We define $Y = \sum_{q=1}^{Q}\sum_{i=1}^{M_s} Y_{q,i}$ which has a gamma distribution M_s degrees of freedom with PDF [30]

$$p_y(y) = \prod_{q=1}^{Q}\frac{\beta_1^{M_s}}{\sigma^{2M_s}_{y_q}}\sum_{k=0}^{\infty}\frac{\delta_k\, y^{QM_s+k-1}}{\beta_1^{QM_s+k}(QM_s+k-1)!}e^{-\frac{y}{\beta_1}},$$

where

$$\delta_k = \frac{1}{k+1}\sum_{i=1}^{k+1}\delta_{k+1-i}M_s\sum_{j=1}^{Q}\left(1-\frac{\beta_1}{\sigma^2_{y_q}}\right)^i,$$

$\beta_1 = \min\{\sigma^2_{y_q}\}$ and $\delta_0 = 1$. Moreover, the distribution of $X = \sum_{m=1}^{M}\sum_{i=1}^{M_s} X_{m,i}$ is found in Lemma 3. By marginalizing over the random variable Y, the CDF of the $\text{SINR}_{\text{ST}} = \frac{X}{1+Y}$ can be calculated as

$$\begin{aligned} P\{\text{SINR}_{\text{MA}} < \gamma\} &= \int_0^\infty \Pr\{X < \gamma+\gamma y\}\, p_y(y)\,dy\\ &= 1-\sum_{m=1}^{M}D_m\gamma^{M_s-1}\int_0^\infty (1+y)^{M_s-1}e^{-\frac{\gamma(1+y)}{\sigma^2_{x_m}}}\,p_y(y)\,dy\\ &= 1-\sum_{m=1}^{M}D_m\gamma^{M_s-1}\sum_{k=0}^{\infty}V_k\int_0^\infty (1+y)^{M_s-1}\\ &\quad\times e^{-\frac{\gamma(1+y)}{\sigma^2_{x_m}}}\,y^{QM_s+k-1}e^{-\frac{y}{\beta_1}}\,dy\\ &= 1-\sum_{m=1}^{M}D_m\gamma^{M_s-1}\sum_{k=0}^{\infty}V_k\sum_{i=0}^{M_s-1}\binom{M_s-1}{i}\\ &\quad\times\frac{(i+QM_s+k-1)!\,e^{-\frac{\gamma}{\sigma^2_{x_m}}}}{\left(\frac{1}{\sigma^2_{x_m}}+\frac{1}{\beta_1}\right)^{i+QM_s+k}}. \end{aligned} \tag{60}$$

Using Taylor series for expansion of $(1+y)^n$, the closed-form solution for integral in (60) is obtained as (25).

Appendix IV
Proof of Proposition 6

The Lagrangian of the problem stated in (41) is

$$L(P_{0,1},\ldots,P_{N,N+1}) = \sum_{n=1}^{N+1}P_{n-1,n} + \lambda f(P_{0,1},\ldots,P_{N,N+1}), \tag{61}$$

where the function f in (40) can be rewritten as

$$\begin{aligned} &f(P_{0,1},\ldots,P_{N,N+1})\\ &= \left[\sum_{n=1}^{N+1}\frac{\gamma_{\text{th}}\mathcal{N}_0 W}{P_{n-1,n}\sigma^2_{n-1,n}}\right] + \frac{\gamma_{\text{th}}}{P_{k-1,k}\sigma^2_{k-1,k}}\sum_{u\in\mathcal{U}_k}P_{u-1,u}\sigma^2_{u-1,n}\\ &+ \sum_{\substack{n=1,n\neq k\\ k\in\mathcal{U}_n}}^{N+1}\frac{\gamma_{\text{th}}}{P_{n-1,n}\sigma^2_{n-1,n}}P_{k-1,k}\sigma^2_{k-1,n}. \end{aligned} \tag{62}$$

To satisfy KKT conditions, we have

$$\frac{\partial L(P_{0,1},\ldots,P_{N,N+1})}{\partial P_{k-1,k}} = 1+\lambda\frac{\partial f(P_{0,1},\ldots,P_{N,N+1})}{\partial P_{k-1,k}} = 0, \tag{63}$$

for $k = 1,\ldots,N+1$, where

$$\begin{aligned} &\frac{\partial f(P_{0,1},\ldots,P_{N,N+1})}{\partial P_k}\\ &= \frac{-\gamma_{\text{th}}\mathcal{N}_0 W}{P^2_{k-1,k}\sigma^2_{k-1,k}} + \frac{-\gamma_{\text{th}}}{P^2_{k-1,k}\sigma^2_{k-1,k}}\sum_{u\in\mathcal{U}_k}P_{u-1,u}\sigma^2_{u-1,n}\\ &+ \sum_{\substack{n=1,n\neq k\\ k\in\mathcal{U}_n}}^{N+1}\frac{\gamma_{\text{th}}}{P_{n-1,n}\sigma^2_{n-1,n}}\sigma^2_{k-1,n}\\ &= \frac{-\rho_k^{\text{out}}}{P_{k-1,k}} + \sum_{\substack{n=1,n\neq k\\ k\in\mathcal{U}_n}}^{N+1}\frac{\gamma_{\text{th}}}{P_{n-1,n}\sigma^2_{n-1,n}}\sigma^2_{k-1,n}. \end{aligned} \tag{64}$$

Combining (63) and (64), we have

$$1-\lambda\frac{\rho_k^{\text{out}}}{P_{k-1,k}} + \sum_{\substack{n=1,n\neq k\\ k\in\mathcal{U}_n}}^{N+1}\frac{\gamma_{\text{th}}}{P_{n-1,n}\sigma^2_{n-1,n}}\sigma^2_{k-1,n} = 0, \tag{65}$$

for $k = 1,\ldots,N+1$.

To find the optimal power coefficients, we need one more equation. Assuming that the equality in the first constraint in (41) is satisfied, we have

$$\sum_{n=1}^{N+1} \rho_n^{\text{out}} = \rho_{\text{des}}. \tag{66}$$

Using (63) and (64), we have $N+2$ equations and $N+2$ unknown, and thus, the optimal solution of the problem stated in (41) can be obtained. To get a more specific solution, from (63) and (64), the Lagrange multiplier can be computed as

$$\lambda = \frac{\sum_{n=1}^{N+1} P_{n-1,n}}{\rho_{\text{des}} - \sum_{i=1}^{N+1} P_{i-1,i} \sum_{\substack{n=1, n\neq i \\ i\in\mathscr{U}_n}}^{N+1} \frac{\gamma_{\text{th}}}{P_{n-1,n}\sigma_{n-1,n}^2} \sigma_{i-1,n}^2}. \tag{67}$$

Next, we substitute λ from (67) into (65), and we get (42).

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